



Field-emission properties of self-assembled Si-capped Ge quantum dots

S.W. Lee^a, Y.L. Chueh^a, H.C. Chen^a, L.J. Chen^{a,*}, P.S. Chen^b, L.J. Chou^a, C.W. Liu^c

^a Department of Materials Science and Engineering, National Tsing Hua University, Hsinchu, Taiwan, Republic of China

^b Department of Materials Science and Engineering, Ming Hsin University of Science and Technology, Hsinchu, Taiwan, Republic of China

^c Electronics Research and Service Organization, Industrial Technology Research Institute, Hsinchu, Taiwan, Republic of China

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Abstract

Field-emission characteristics of self-assembled Si-capped Ge quantum dots on Si (001) with different Si coverages have been investigated. During capping with Si, Ge quantum dots exhibit a dramatic shape transition from multi-faceted domes to truncated pyramids, and eventually to nanorings. With an appropriate amount of Si-capping to form the truncated pyramids, the field-emission behaviors of Si-capped Ge quantum dots were found to be improved significantly. Based on transmission electron microscope examinations, this improvement can be attributed to the sharper apex of the truncated pyramids as compared to the uncapped domes. However, further Si-capping could degrade the field-emission properties owing to the flattening of Ge islands features. This work provides a useful scheme to utilize self-assembled Si-capped Ge quantum dots as field-emitter arrays.

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1. Introduction

Strain-induced self-assembled Ge quantum dots (QDs) on Si(001) have attracted considerable interest for the promising applications in future optoelectronic devices compatible with Si technology [1–5]. In addition, the regularly distributed, quantum-sized Ge QDs may be useful in a range of technological applications, such as field-emitter arrays. Recently, Tondare et al. had reported the feasibility of using the self-assembled Ge islands on Si(111)-7 × 7 as field-emitters [6]. It was found that the two-dimensional QDs arrays exhibited a low onset voltage for field-emission with the high current stability.

For practical applications relying on a quantum confinement, the Ge QDs usually undergo a Si-capping process to be embedded in a semiconductor matrix [7]. In the previous investigation of the evolution of the Ge QDs during the initial stages of Si encapsulation up to 28 equivalent monolayers (eq-MLs, 1 eq-ML = 6.27×10^{14} atom/cm²) [8], drastic changes of shape and surface morphology of the Ge QDs have been observed [9]. In this work, the field-emission characteristics of self-assembled Ge QDs on Si(001) at different Si coverage are

investigated. With an appropriate amount of Si-capping, the field-emission behaviors of Si-capped Ge QDs were found to be improved significantly. On the other hand, further Si-capping could degrade the field-emission properties. These results are closely correlated with the surface geometry of Si-capped Ge QDs during Si overgrowth and will be discussed in this paper.

2. Experimental procedures

10–25 Ω cm, 100 mm diameter *p*-type (001)-oriented Si wafers were used in the present study. All the Ge QDs investigated in this work were grown at 600 °C in a commercially available multi-wafer ultra-high vacuum chemical vapor deposition (UHV/CVD) system. Pure SiH₄ and 5% GeH₄ diluted in He were used as precursors. The Si wafers were dipped in a 10% HF solution to achieve a hydrogen-passivated silicon surface, and then transferred into the UHV/CVD system. A 60-nm-thick Si buffer layer was first grown. After depositing the Si buffer, a 13.1 eq-ML Ge layer was then deposited to form the self-assembled QDs under Stranski–Krastanov (SK) growth mode [10]. To investigate the field-emission properties of the self-assembled Ge QDs during the Si overgrowth, the coverages of Si-capping layer on Ge islands were chosen to be 0, 14, 21, 28 and 56 eq-MLs. As the deposition was terminated, the wafers were kept in the

* Corresponding author.

E-mail address: ljchen@mx.nthu.edu.tw (L.J. Chen).

deposition chamber for 3 min, unless otherwise specified, to evacuate the residual reactant, and were then removed from the chamber.

The Ge dot shape and size distribution were characterized ex situ by atomic force microscopy (AFM) in tapping mode. Both plan view and cross-section transmission electron microscopy (XTEM) images revealed more detailed information about diameter and facets of the Ge nanostructures. TEM in conjunction with an energy dispersion spectrometer (EDS) was utilized to determine the composition of Ge nanostructures. The electron field-emission characteristics were measured under a pressure of 1×10^{-7} Torr in a scanning-probe field-emission system. The substrate was stationary, while a spherical stainless-steel probe of 1 mm in diameter as anode was installed on a three-axis motorized manipulator. The lowest emission current is recorded in the level of nA. The measurement distance between the anode and emitting surface was fixed at 100 μm . The I – E curves were recorded after several electron emission cycles.

3. Results and discussion

3.1. Shape transition of Si-capped Ge QDs

The AFM images in Fig. 1 illustrate the shape evolution of the Ge QDs during the overgrowth with 0 to 28 eq-MLs of Si. For an uncapped sample, Fig. 1(a) shows the well-known bimodal islands, pyramids with shallow {105} facets and domes with higher angle {113} facets, which are commonly observed for high temperature deposition [10,11]. About 88% of the Ge QDs are domes; the rest are pyramids. After deposition of 14 eq-MLs Si on Ge QDs, the pyramids are dominant and the domes are hardly seen, as shown in Fig. 1(b). In the meantime, the density of the QDs increased from about

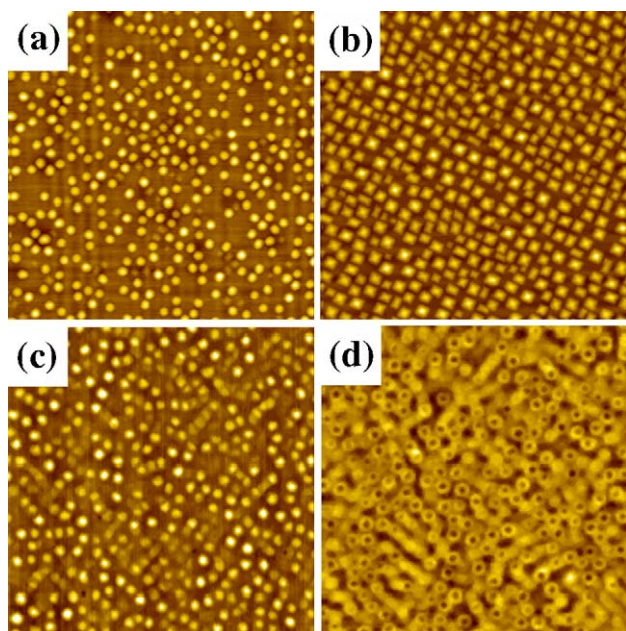


Fig. 1. AFM images ($2 \mu\text{m} \times 2 \mu\text{m}$) of Ge QDs capped with (a) 0, (b) 14, (c) 21 and (d) 28 eq-MLs of Si.

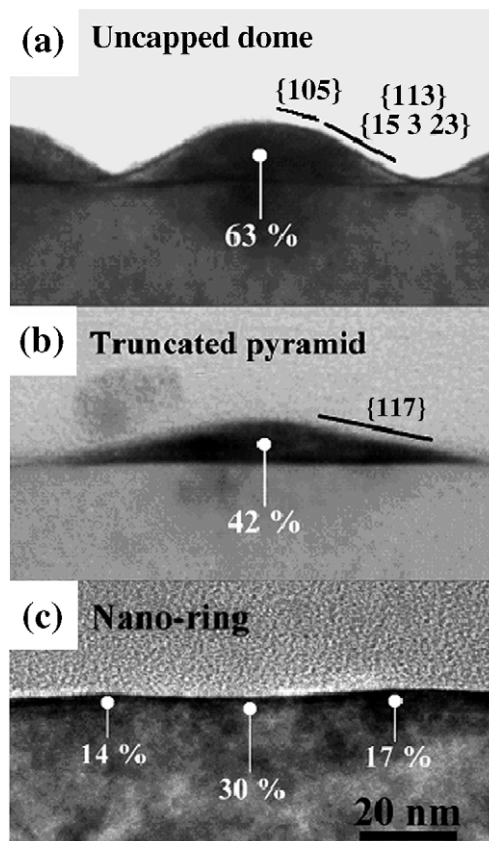


Fig. 2. XTEM images of the Ge QDs (a) without and capped with (b) 14 eq-MLs and (c) 28 eq-MLs of Si. (a) and (c) are viewed along [011] Si direction. The image in (b) was taken along [010] direction so that the profile of the pyramid base can be seen. The percentages marked in the figures refer to percentages of Ge determined by EDS.

9×10^9 to $1.1 \times 10^{10} \text{ cm}^{-2}$ with a broader island-size distribution. The dome to pyramid shape transition of Ge QDs has been reported by Rastelli et al. [12]. This phenomenon was interpreted in terms of the dependence of equilibrium shape of QDs on their volume and composition as a result of intermixing.

After growth of 21 eq-ML Si as shown in Fig. 1(c), some small QDs disappear and the large QDs decrease further in height and diameter with a density of $7.9 \times 10^9 \text{ cm}^{-2}$. Fig. 1(d) shows the surface morphology after deposition of 28 eq-MLs Si. At this stage, the ring-like islands (nanorings) appeared to replace the larger QDs in the images shown. These nanorings have an average height and diameter of 1.2 ± 0.5 and $65 \pm 6 \text{ nm}$, respectively, with full-width half-maximum measured to be $35 \pm 5 \text{ nm}$. The previous results demonstrate that the formation of nanorings is closely correlated with a strain-driven process. The detailed formation mechanism and control of these nanorings were reported elsewhere [9]. For further deposition with 56 eq-MLs Si-capping layer, the nanorings tended to smooth out and were no longer evident in the AFM images.

3.2. Microstructures of Si-capped Ge QDs

Fig. 2(a), (b) and (c) show XTEM images of the uncapped domes, truncated pyramids and nanorings, respectively. It is

evident that Ge QDs reduced its heights and aspect ratios with the increase of Si coverage. This evolution indicates that the intermixing between Si and Ge QDs tends to develop the stable (001) surface to replace the higher angle facets with higher energy. The facets bounding those Si-capped QDs were identified by XTEM and AFM. As shown in Fig. 2(a), the intermediate surface of Ge domes is bounded by {113} facets with an inclination of 25.2° and {15 3 23} with an inclination of 33.6° , while the apex and base are composed of {105} facets with an inclination of 11.3° [13]. A small (001) facet is also observed at the apex for some uncapped domes. After growth of 21 eq-MLs Si, the uncapped domes transform dramatically to the truncated pyramids. As shown in Fig. 2(b), these truncated pyramids were bounded by shallow facets inclined by 13.9° , which we identify as {117}. With the increase of Si-capping layer to 28 eq-MLs, the nanorings appeared and Ge QDs were almost flattened due to the serious intermixing, as shown in Fig. 2(c). EDS measurement data as illustrated in the figures also indicate that substantial intermixing of Si and Ge occurred during the formation of the nanorings.

3.3. Field-emission properties of Si-capped Ge QDs

Fig. 3 shows the field-emission ($F-E$) characteristics for the uncapped domes, truncated pyramids and nanorings, respectively. The $I-E$ characteristics were measured repeatedly to obtain the stable and reproducible $I-E$ characteristics. The steps observed in the $I-E$ curves may be related to the difference in work functions for different facets and the size fluctuation of Si-capped Ge dots. The turn-on field, defined at a current density of $10 \mu\text{A}/\text{cm}^2$, decreased from $7.5 \text{ V}/\mu\text{m}$ for uncapped Ge QDs to $6.5 \text{ V}/\mu\text{m}$ for Ge QDs capped with 14 eq-MLs Si. It is well known that the turn-on voltage strongly depends on the sharpness of the field-emitters [14]. As mentioned above, the {105} facets at the apex of the uncapped domes were replaced by the higher angle, steeper {117} facets after the overgrowth of 14 eq-MLs Si. Therefore, this improved turn-on field can be attributed to the sharper apex of the truncated pyramids as compared to the uncapped domes. It is worthwhile to note that uncapped domes have a much higher aspect ratio than that of truncated pyramids. On the other hand, the sample with nanorings exhibits a very high turn-on field up

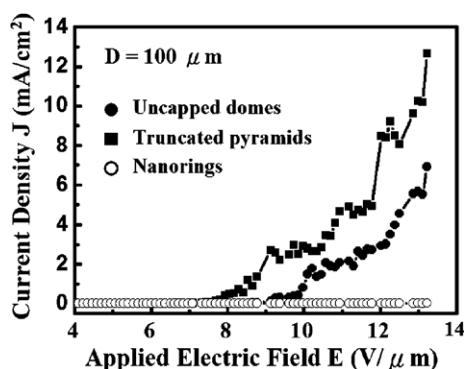


Fig. 3. Plots of field-emission current density J (mA/cm^2) against local applied field E ($\text{V}/\mu\text{m}$) curves for the Ge QDs capped with different thickness of Si.

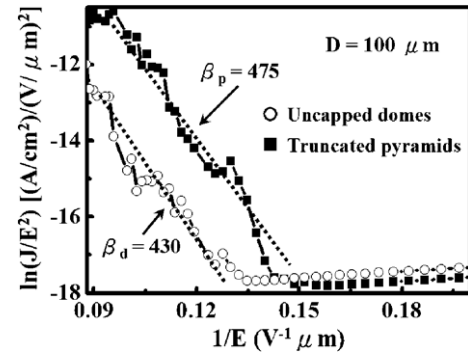


Fig. 4. Fowler–Nordheim plots of self-assembled Ge QDs without (multi-faceted domes) and capped with 14 eq-MLs Si (truncated pyramids).

to $15 \text{ V}/\mu\text{m}$. It is likely to be associated with serious flattening of Ge QDs features after the Si overgrowth.

Fig. 4 shows the Fowler–Nordheim ($F-N$) plots [$\ln(J/E^2)$ vs $1/E$] for the uncapped domes and truncated pyramids [15,16]. The $\ln(J/E^2) - 1/E$ plot gives the straight lines at high fields for both uncapped and Si-capped Ge QDs emitters, suggesting the Fowler–Nordheim tunneling process. The small change in slope of the $F-N$ plot at higher fields may be attributed to the limited supply of electrons within the Ge dots [17]. The field enhancement factor β , which is used to indicate the degree of the field-emission enhancement of any tip shape on a planar surface, can be roughly calculated based on the average slope of $F-N$ plot shown in the Fig. 4. The truncated pyramids were found to possess a β value of 475, which is higher than that of the uncapped Ge domes, 430. This result is not only consistent with our XTEM observation, but also demonstrates the feasibility of using self-assembled Si-capped Ge QDs “truncated pyramids” as field-emitter arrays.

4. Summary and conclusions

In summary, field-emission characteristics of self-assembled Ge QDs on Si(001) have been investigated at different Si coverages. With an appropriate amount of Si-capping on Ge QDs, the turn-on field for emission was found to decrease significantly. Based on the results of XTEM and AFM observation, this improvement can be attributed to the sharper apex of the truncated pyramids as compared to the uncapped domes. In addition, the truncated pyramids were found to possess a higher field enhancement factor β than that of the uncapped Ge domes. However, further Si-capping could degrade the field-emission properties because of the flattening of Ge islands features. This work provides a useful scheme to utilize self-assembled Si-capped Ge quantum dots as field-emitter arrays.

Acknowledgments

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